Fermi National Accelerator Laboratory

FERMILAB-Conf-95/100

2 x 2 TeV $\mu^+\mu^-$ Collider: Lattice and Accelerator-Detector Interface Study

N.M. Gelfand and N.V. Mokhov

Fermi National Accelerator Laboratory
P.O. Box 500, Batavia, Illinois 60510

May 1995

Presented at the *1995 Particle Accelerator Conference*, Dallas, Texas, May 1-5, 1995

Operated by Universities Research Association Inc. under Contract No. DE-AC02-76CHO3000 with the United States Department of Energy

2×2 TeV $\mu^+\mu^-$ Collider: Lattice and Accelerator–Detector Interface Study*

N. M. Gelfand and N. V. Mokhov

Fermi National Accelerator Laboratory

P.O. Box 500, Batavia, Illinois 60510

May 10, 1995

Abstract

The design for a high-luminosity $\mu^+\mu^-$ superconducting storage ring is presented based on first-pass calculations. Special attention is paid to two low-β interaction regions (IR) whose optics are literally interlaced with the collider detectors. Various sources of backgrounds in IR are explored via realistic Monte Carlo simulations. An improved design of the collider lattice in the neighborhood of the interaction points (IP) is determined by the need to reduce significantly background levels in the detectors.

*Presented at the *1995 Particle Accelerator Conference*, Dallas, Texas, May 1-5, 1995

1 INTRODUCTION

An increasing interest to a high-energy high-luminosity $\mu^+\mu^-$ collider project [1, 2] is based on the high physics potential of such a machine [3] beyond what can be accomplished at e^+e^- and pp (LHC) colliders. Even though there are some problems to be examined, especially on a technical side, no obvious show stopper has yet been found [4]. The collider complex will consist of a few essential parts: a high-intensity rapid-cycling 10 to 30 GeV proton synchrotron, muon production and muon cooling sections, a cascade of re-circulating linacs, and a 2-TeV storage ring providing collisions in two low-β regions with a luminosity $\approx 10^{34}cm^{-2}s^{-1}$. This paper deals with a prototype design for the final stage, 2×2 TeV collider. This is, to our knowledge the first complete lattice of the 2×2 TeV collider with a β^* of 3mm [5]. Muon decay and beam loss induced backgrounds in the collider detectors have the potential of killing the whole concept unless there is significant suppression via special shielding in the vicinity of the detector [6]. Here we continue collider/detector interface study to mitigate further this problem.

2 LATTICE DESIGN

This is a geometric design, that is the beam energy does not enter into the properties of the elements of the design. At the muon beam energy of 2 TeV, and with superconducting dipoles of $\approx$8T the circumference of the ring is $\approx$6km, which corresponds to $\approx$ 1000 turns for the $\approx$25ms beam lifetime. This model design has been constrained as follows [5]:

- it uses magnets which are reasonable extrapolation from existing superconducting magnets;
- the β^* at the interaction point be 3mm in both planes;
- the dispersion, η at the interaction point be zero;
- the lattice has two low-β IRs and two long high-β utility straight sections;
- the lattice functions at the end of the insertions, low-β and high-β, be matched with the lattice functions in the arcs.

Lattice design calculations are done with the MAD and TEVLAT codes [7]. The design of a dispersion killer is most inexpensively done if the phase advance of the standard cell is either 60^0 or 90^0. We have chosen a 60^0 phase advance for the standard cell. The other parameter for the standard cell is β_{max}. In principle this is arbitrary but in order to match the low-β insertion into the arcs we found it better use a relatively low β_{max} of 75m. With a more elaborate IR it would be possible to use a larger value. The advantage of a larger value might be to increase the packing fraction, the percentage of the ring filled with dipoles, and hence reduce the cost, and the length. With β_{max}=75m the packing fraction in the standard cell is 91%.

The design of the utility straights is straight forward using the idea of matching quads due to Tom Collins. The β at the middle of the straight is 200m but can be adjusted within reasonable limits. Within the utility straight the maximum β is $\approx$300m. The dispersion across the utility straight is matched by having dispersion killers at each end of the straight. This, of course, lengthens the ring, and if a zero dispersion straight is not needed then perhaps a different design could be developed. The designed the low-β IR matches to the arcs. The parameters of the quadrupoles are shown in Table 1 for (Bρ)=6671.28139 at 2 TeV.

Table 1 : Quadrupole parameters in the arc FODO cells, utility straight sections, low-β triplets, and IR/FODO matching sections. F=(G/(Bρ))$^{1/2}$(m^{-1}).

Sector	Name	Length(m)	F	G(T/m)
FODO	QF1	1.257	0.1929	248.2569
Utility	QFC1	4.200	0.1306	113.7638
	QF2	4.200	0.1235	101.8044
	QF3	4.200	0.1462	142.5645
Low-β	QFT1	3.467	0.1982	262.0556
	QFT2	7.548	0.1982	262.0556
	QFT3	3.762	0.1982	262.0556
Matching	QFM1	2.769	0.0794	42.0365
	QFM2	2.859	0.0932	57.9832
	QFM3	5.166	0.1823	221.7979
	QF1X	0.066	0.1929	248.2569

The tunes for this lattice depend on the number of FODO cells in the arcs and can be adjusted with correction quadrupoles. The natural chromaticity, that is the chromaticity with no sextupole correctors, is very large with $\zeta_x \approx \zeta_y \approx$ -3500, that comes from the low-β insertions. One can correct this chromaticity with correctors in the arcs in which case one needs very strong sextupoles $B''/(B\rho)$ $\approx$4, to be compared with the values, $B''/(B\rho) \approx 4\times10^{-2}$, typically used in the Tevatron to correct and control the chromaticity. Sextupoles in the insertions cannot be used to correct the chromaticity because of the zero dispersion in the insertions.

3 APERTURES AND IMPERFECTIONS

The current lattice design has no non-linear elements or imperfections. The stable region will have a non-zero value for the non-integer part of the tune. With a chromaticity of $\approx$-3500 this yields a full width for the *momentum aperture* of $\approx$ 1/3500 or $\approx 2.8\times10^{-4}$. This has been confirmed with a modeling code. With the chromaticity correcting sextupoles third integer values of the tune become unstable as well as integer values. In addition the chromaticity is now non-linear. Model calculations indicate that the momentum aperture is reduced by perhaps a factor of 2.

For the linear lattice the *dynamic aperture* is given by the value of β in the physical aperture. At the maximum value of β in the lattice, which occurs in the inner triplet, of $\approx 2\times10^5$m (200km) and a radius for the physical aperture of 80mm as in [2, 4, 6], the maximum normalized emittance is $\approx$ 600π mm mr. Using in addition the results of shower simulations ([6] and the following section) and a realization of the problems with large, very high field magnets, we have found that 45mm radius aperture in the triplet ($\pm$110m from the IP) and 25mm radius aperture in the rest of the ring is an optimal choice. The size of the dynamic aperture has been confirmed by tracking calculations. The dynamic aperture is not restricted by the values of the chromaticity sextupoles.

An ideal lattice is described here, i. e. a lattice whose components have precisely the strengths given by the lattice design code. Further calculations based on a model with magnet errors are obviously needed. One point is interesting however. The $\mu^+\mu^-$ collider is the only collider where one can track for the full life time of the beam ($\approx$1000 turns) using a reasonable amount of computer time.

Imperfections in the magnets in the low-β quadrupoles will result in a mismatch in the lattice functions and will generate a "β wave". One can get an idea of the magnitude of the problem by looking at the lattice functions for a off-momentum particle.

Figure 1 shows the lattice functions in the low-β region for particle of nominal momentum. The maximum value of β is $\approx$200km. For a Δp/p of 10^{-5} (this value of Δp/p is equivalent to changing the strengths of all the quadrupoles in the ring by 5×10^{-6}) the maximum value of β is somewhat smaller ($\approx 17.5\times10^4$m) and β^* is

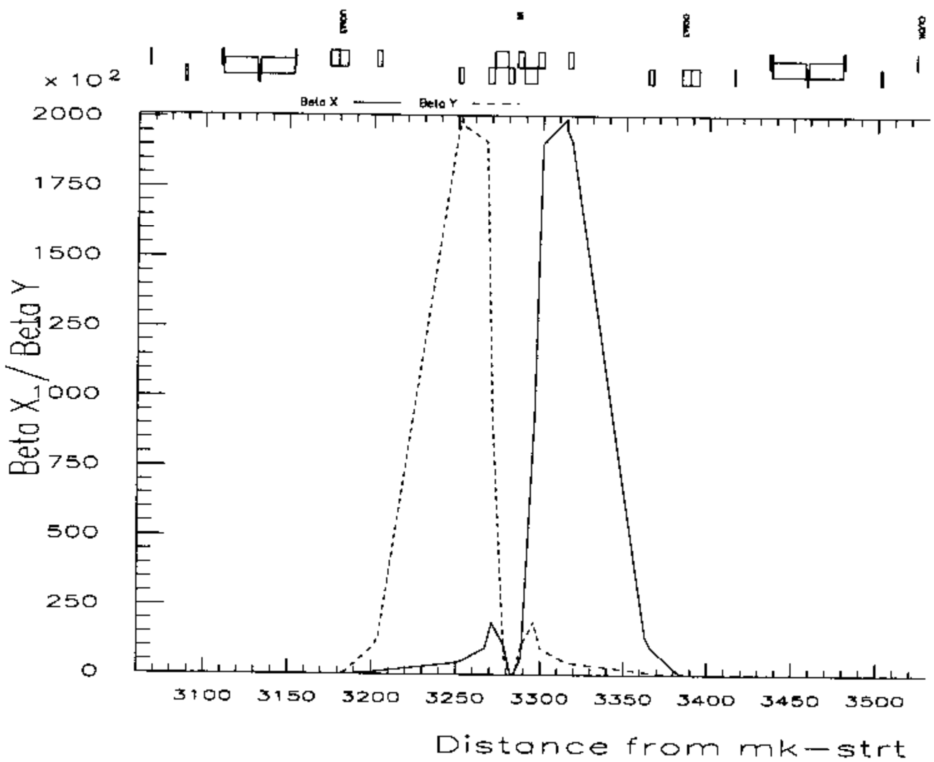

Figure 1: Beta functions in the interaction region

increased to 3.5mm. In the arcs a strong "β wave" appears, which does not cause a loss of dynamic aperture. The effect of the momentum offset in the utility straights is negligible. One infers from this that if we want the lattice to match then we will need to control the strengths of the low-β quads to $\approx 10^{-6}$.

4 BACKGROUNDS

Shower simulations are done with the MARS code [8]. The calculations include forced muon decays, the tracking of electrons with emission of the synchrotron photons along the track, the simulation of electromagnetic showers in the accelerator and detector components induced by electrons and synchrotron photons hitting the beam pipe, and simulation of muon interactions in the lattice and detector including electromagnetic showers originating from those interactions. The 3-D geometry and magnetic fields in the triplet and in the model detector are used. Fig. 2

shows the γ and e^+e- spectra in the lattice elements closest to the IP. Note the very high energy of decay electrons $\approx$1 TeV and photons $\approx$1 GeV, and enormous number of those photons.

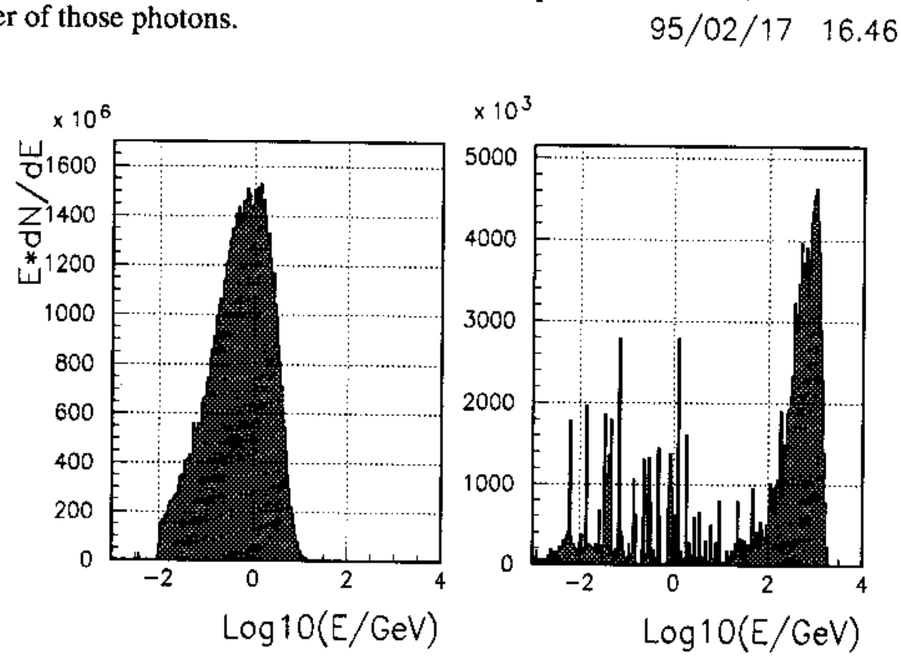

Figure 2: Photon (left) and electron/positron (right) energy spectra in the inner triplet accelerator components

Due to the energetic showers, a source term for backgrounds in the central detectors is extended over hundred meters from the IP. As was found in [6] the most efficient way to suppress background levels is a collimation as close to the detector as possible. Especially helpful is a very small tapered aperture tungsten nozzle sitting in the 0.15–1.2m region from the IP with the low-β quadrupole starting at 1.2m inside the detector. Figure 3 shows charged particle fluxes in the central tracker per crossing of two 10^{12} muon beams. Fluxes are dropping rapidly with distance from the beam axis, but at the flux maximum these are unacceptably high.

One sees that with the tungsten nozzle the fluxes are significantly reduced. With additional collimators in the triplet the overall effect can be as high as a factor of 500, with maximum hit rate of order of 200–400 cm^{-2}. Further reduction is possible with a suppression of synchrotron photon production by keeping the high field dipoles as far from the IP as possible. Results for the lattice [6] with a dipole field in the triplet turned off are shown in Fig. 3. Backgrounds in the part of the tracker toward the ring center are thousands times lower. On the outside the reduction is

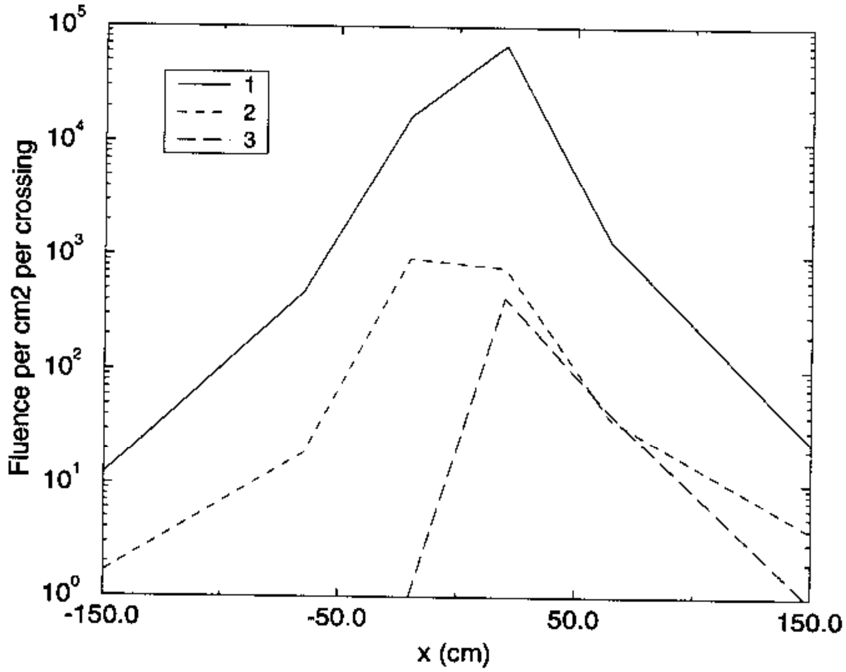

Figure 3: Distribution of e^+e^- flux in the central tracker horizontal plane. 1 – no collimation, 2 – with tungsten nozzle, 3 – dipole field turned off in the triplet

about a factor of 2 to 5. This approach is incorporated into the proposed lattice where the nearest dipole starts at 130m from the IP. Figure 4 shows a contribution to energy deposition in the cental tracker ($6 \leq r \leq 100$cm) from muon decays along the IR. The existence of long drifts in the proposed lattice, gives possibilities for a collimation and spoiling in a vicinity of the detector.

The detector muon system can be protected from low-energy large-angle particles created along the lattice with a shielding wall at $\approx$20m. Its efficiency for the reduction of showers and neutrons can be as high as required. As for the muon component other measures are needed such as a beam scraper system well upstream of the IR.

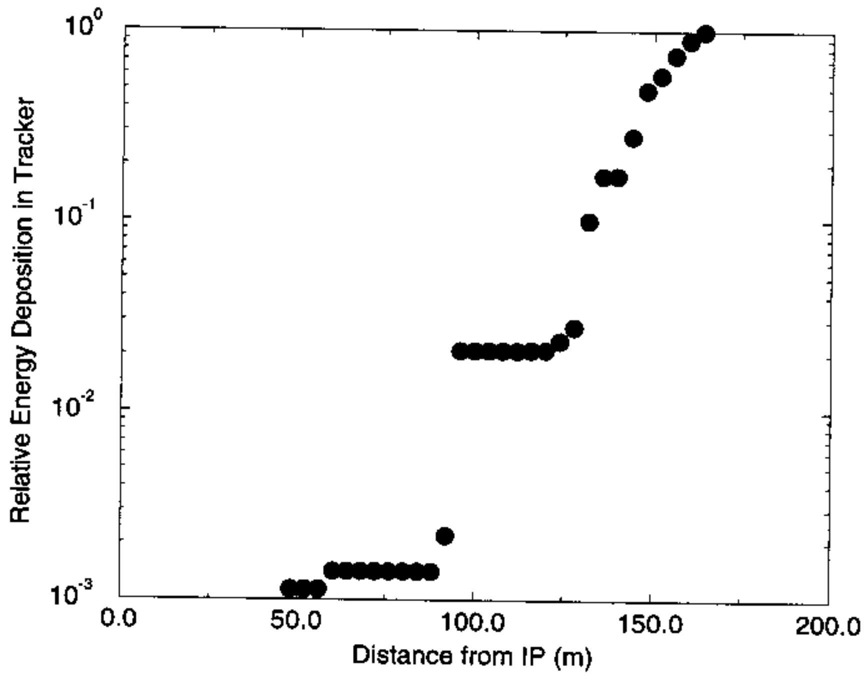

Figure 4: Cumulative energy deposition in the central tracker as a function of shower origin coordinate

5 HEAT LOAD TO SC MAGNETS

Due to muon decays $\approx$ 30 Joules of energy are deposited in every meter of the ring. With the 10 to 30 Hz repetition rate this results in a heat load which significantly exceeds the levels tolerated in existing superconducting (SC) magnets. Our calculations show that in addition the peak energy deposition in the coils exceeds the quench limit. The problem is especially serious in the β_{peak} region. The way to mitigate this would be to intercept most of the shower energy at the nitrogen temperature level by inserting a liner between the beam pipe and the SC coils. We found that a copper liner does a good job. With the coil apertures defined above, the liner occupies the region between 10 and 25mm in the arcs, and 30 and 45mm in the triplet. Further optimizations are certainly required.

6 CONCLUSIONS

A prototype lattice for a $\mu^+\mu^-$ collider has been constructed. The dynamic aperture is determined. The momentum aperture is found first by the chromaticity of the lattice, and if the chromaticity is corrected by sextupoles, by the third order resonance. The practical physical aperture with a 15-mm copper liner is determined compatible with beam dynamics, detector performance and heat load in the SC magnets. The effect of the IR scheme on particle fluxes in the collider detector has been studied.

References

[1] E. A. Perevedentsev, and A. N. Skrinsky, in *Proc. 12th Int. Conf. on High Energy Accelerators*, F. T. Cole, and R. Donaldson, eds., p. 485 (1983); A. N. Skrinsky, and V. V. Parkhomchuk, *Sov. J. of Nucl. Physics*, **12**, p. 3 (1981).

[2] D. V. Neuffer, and R. B. Palmer, "A High-Energy High-Luminosity $\mu^+\mu^-$ Collider", *BNL-61267, CAP-109-Muon-94C*, June 1994.

[3] V. Barger et al., "Physics Goals of a $\mu^+\mu^-$ Collider", *BNL-61593, CAP-118-Muon-94C*, March 1995.

[4] R. B. Palmer et al., "Beam Dynamics Problems in a Muon Collider", *BNL-61580, CAP-120-Muon-95J*, March 1995.

[5] N. M. Gelfand, "A Prototype Lattice Design for a $\mu^+\mu^-$ Collider", *Fermilab TM-1933*, April 1995.

[6] G. W. Foster, and N. V. Mokhov, "Backgrounds and Detector Performance at a 2×2 TeV $\mu^+\mu^-$ Collider", *FERMILAB-Conf-95/037*, March 1995.

[7] N. M. Gelfand, and A. D. Russell, "TEVLAT", Fermilab (1990); H. Grote, and F. C. Iselin, "The MAD Program User's Reference Manual", Version 8.1, *CERN/SL/90-13 (AP)* (1990).

[8] N. V. Mokhov, "The MARS Code System User's Guide, Version 13(95)", *Fermilab FN-628*, April 1995.